Simulation of the Compression of a Magnetized Plasma with Liquid Metal

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General Fusion is working to demonstrate the viability of a novel magnetized target fusion (MTF) approach, wherein a compact toroid (CT) plasma is compressed with an acoustic pulse [1,2]. The CT is fired from a tapered injector into an evacuated cylindrical vortex inside a spherical volume of rotating liquid metal (PbLi). A compression cycle begins with an energy input of approximately 100 MJ from an array of pneumatically driven pistons that strike the outer surface of the reactor sphere, launching a high-pressure acoustic pulse into the liquid metal, which propagates inwards and compresses the CT to fusion conditions. At maximum compression, deuterium-tritium fusion reactions liberate neutrons that scatter in the lead and are absorbed by the lithium to breed more tritium. Heat is extracted from the liquid metal to produce steam for the pistons as well as electricity.

The complexity of the liquid-plasma interaction, coupled with inaccessibility of the interface to diagnostic equipment, necessitates detailed simulation work that accurately evaluates energy transfer from the acoustic pulse to the plasma. The simulation must address the following physics: plasma evolution during compression with focus on loss of energy confinement as beta limits are exceeded, evolution of the liquid-plasma interface due to Richtmyer-Meshkov and Raleigh-Taylor instabilities, diffusion of the magnetic field into the liquid metal, transport of wall material within the plasma and subsequent radiative quenching of the plasma, heating by alpha particles, and cooling by bremsstrahlung and thermal conductivity. The FLASH code offers many features applicable to evaluating these problems.

The FLASH code is a modular, parallel multiphysics simulation code capable of handling general compressible flow problems typically found in astrophysical environments. The non-ideal MHD equations are solved in three dimensions with a directionally unsplit staggered mesh (USM) algorithm [3], based on a finite-volume, high-order Godunov method combined with a constrained transport (CT) scheme which ensures the solenoidal constraint of the magnetic fields. In this approach, the cell-centered variables such as the plasma mass density, plasma momentum density, and total plasma energy are updated via a second-order MUSCL-Hancock unsplit space-time integrator using the high-order Godunov fluxes. The face-centered magnetic fields are updated using Stokes' Theorem as applied to a set of induction equations, enforcing the divergence-free constraint of the magnetic fields.

Lagrangian 1D simulations of the liquid metal and plasma predict net energy gains between 6.6 and 0.4. However, they do not incorporate the effects of 3D magnetic field topologies and surface instabilities. Initial results generated by FLASH with ideal MHD and simplified physics models show a compression that is not spherically symmetric. New algorithms for anisotropic viscosity, thermal conductivity, and magnetic diffusivity have been developed. Results of net energy gain from 3D simulations with resistive MHD will be presented.

[1] M. Laberge, J. Fusion Energy, 27 (2008) 65.
[2] S. Howard et al., J. Fusion Energy, 28 (2009) 156.
[3] D. Lee, A. Deane, J. Comp. Phys. 228 (2009) 952.